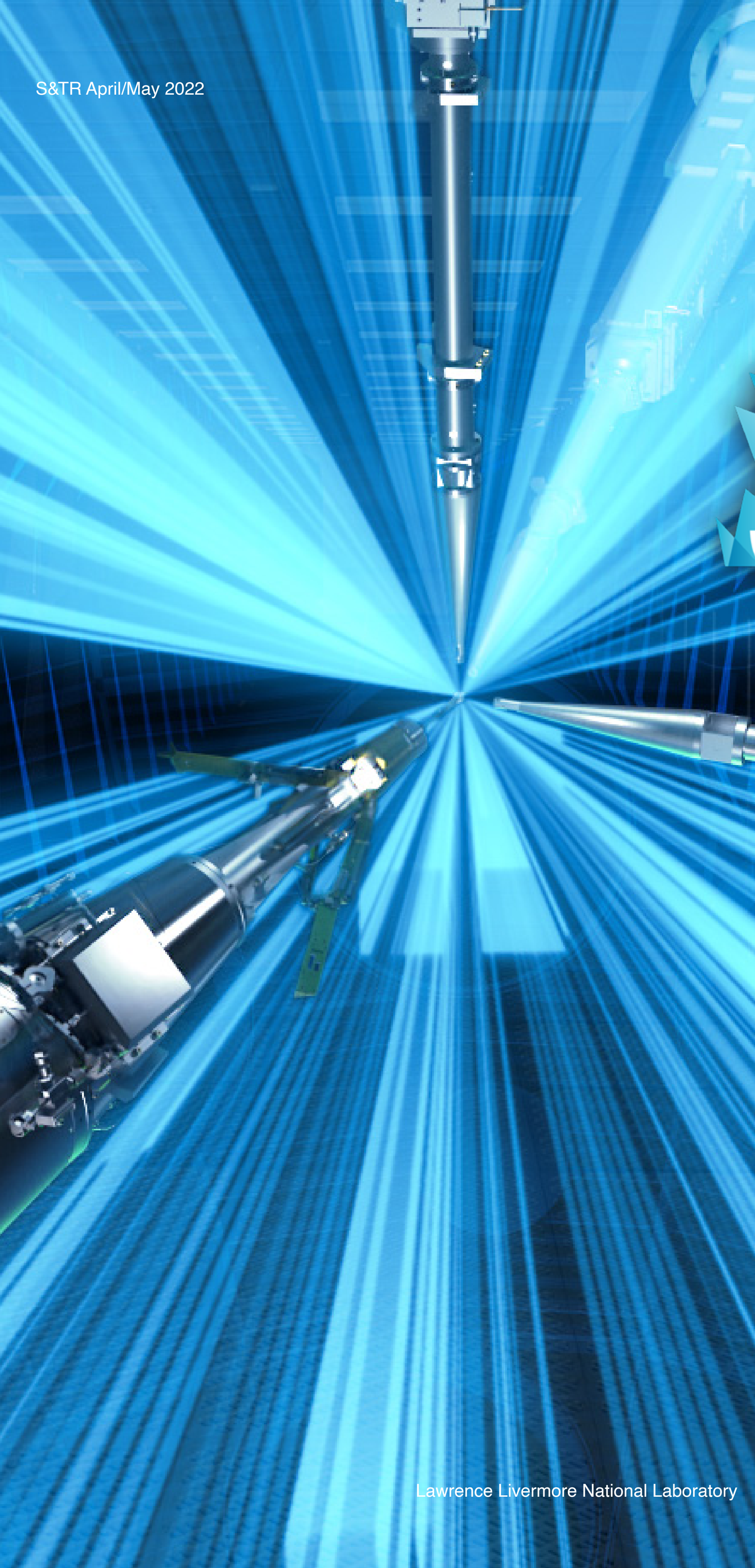
BEAMING WITH EXCELLENCE

After 50 years of pioneering laser research along with experimental and computational advances, the Laboratory and the inertial confinement fusion community stand at the threshold of ignition.



50 Years

HUMANKIND'S history is a tapestry of invention and application, both scientific and technical. From learning to make tools and control fire, to understanding complex astrophysical phenomena and developing ever-more advanced machines, people are continually striving to investigate, innovate, and discover in the pursuit of knowledge. In 2021, Lawrence Livermore researchers and colleagues from collaborating institutions working at the National Ignition Facility (NIF) added another stitch to this tapestry. After millennia of looking up at the stars, humankind now stands at the threshold of replicating one.

Recreating fusion, the process that powers the Sun, within a laboratory has long been a grand challenge of scientific research. On August 8, 2021, the research team conducted a shot that produced a record-breaking 1.3 megajoules (MJ) of fusion energy by imploding a deuterium-tritium (DT) fuel capsule with 1.9 MJ of laser energy. The capsule, located within a hohlraum that converted the laser light into x rays, produced about six times as much fusion energy as the x-ray energy it absorbed. The shot marks the first time in a laboratory that scientists have observed signs of a self-sustaining wave of nuclear reactions—thermonuclear burn—in the DT fuel, opening a fundamentally new regime to explore and advance the Laboratory's critical national security mission and future fusion energy applications.

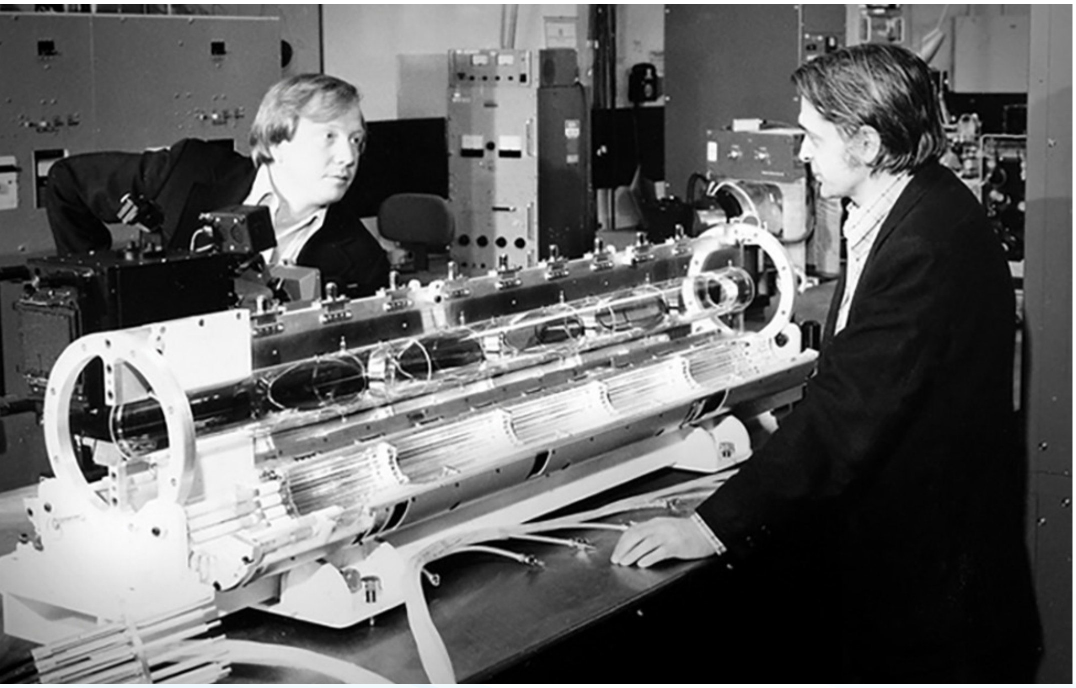
This monumental achievement was the culmination of painstaking efforts undertaken by a team of multidisciplinary experts over multiple decades. Since the inception of Lawrence Livermore's Laser Program 50 years ago, scientists and engineers from across the Laboratory have been at the forefront of scientific and technological innovations that have paved the way to the August 2021 milestone. These advancements were a concerted effort of Livermore and collaborators including industrial and academic partners, Los Alamos and Sandia national laboratories, the University of Rochester's Laboratory for Laser Energetics (LLE), General Atomics, and the Massachusetts Institute of Technology (MIT). Being at the threshold of ignition as defined by the National Academy of Sciences (NAS)—where more energy is produced by the fusion reactions inside the fuel capsule than the amount of laser energy delivered to the target—builds on the work of the entire team, including the people who pioneered inertial confinement fusion (ICF) research since the Laboratory's earliest days.

Driven by Purpose…and Lasers

In the 1950s, Laboratory physicist John Nuckolls and colleagues were investigating whether it was possible to ignite a fusion explosion without a fission bomb as a means of generating power for commercial applications. They ran the latest, state-of-the-art computer codes and found that radiation at temperatures of a few hundred electronvolts (eV) could implode a capsule of DT fuel and initiate a very small-scale fusion explosion. However, the process needed a driver. When physicist and engineer Theodore Maiman demonstrated the first laser in 1960, its implications for other fields of research began to take shape. Nuckolls, who later became Laboratory director, saw the laser as the tool for achieving fusion ignition through ICF, wherein the small mass of DT could be compressed and heated through the laser-driven implosion of the fuel capsule.

"In 1972, John and Livermore colleagues Lowell Wood, Albert Thiessen, and George Zimmerman published a defining set of challenges and requirements that would be faced in trying to achieve an ICF laser-driven implosion," says John Lindl, a senior scientist in the NIF and Photon Science (NIF & PS) Principal Directorate who has been part of Livermore's laser research since he joined the Laboratory in 1972. "Their calculations used an early version of the LASNEX code, which has been enhanced over the years for laser fusion predictions and developing ICF target designs."

Throughout the 1960s, nascent experimental laser research at the Laboratory was disjunct, and progress was slow to develop a high enough power laser for fusion applications. In 1971, Laboratory Director Michael May and Associate Director for Plans Carl Haussmann took steps to consolidate the distributed expertise in ICF code development, specifically LASNEX; laser–plasma interactions (LPIs); and high-power, short-pulse lasers into a single program. Haussmann, the program's first leader, built a crackerjack team with the help of John Emmett, who was head of solid-state laser research at the Naval Research Laboratory and became the Laboratory's Y-Division leader in 1972; and physicist William Krupke from Hughes Aircraft Company.



Physicists John Emmett (left) and John Nuckolls were two of the most influential pioneers of the Laboratory's Laser Program and inertial confinement fusion (ICF) science and technology.

Under their collective leadership, the scope of the Laser Program expanded, the workforce grew, and plans were initiated to construct a series of bigger, more complex, higher energy lasers for achieving ICF, with an eye on developing a 10-kilojoule (kJ) class, 20-beam, solid-state laser called Shiva.

In 1974, the Janus laser came online and was the first Livermore system to carry out target compression experiments for fusion research. Compared to the 1-joule (J), 1-nanosecond (ns, billionth of a second) infrared pulses of early 1970s lasers, Janus was a powerhouse. In its first iteration, the single-beam laser, made from commercially available silicate glass, produced 20 J and 0.2 terawatts (TW) in just 0.1 ns. Later, the addition of a second beam resulted in achieving 40 J. Experiments using Janus were instrumental in demonstrating direct-drive implosion of a spherical DT target—wherein the laser directly irradiates the capsule containing the fuel—and in helping researchers gain insight into the complex physics involved. Janus experiments also led to development of better diagnostics for measuring implosion characteristics and further improving LASNEX.

Janus was followed by the one-beam Cyclops laser in 1975 (developed as a prototype and test bed for Shiva components) and the two-beam Argus laser (designed for direct-drive experiments) the next year, both of which contained neodymium-doped phosphate glass amplifiers. Lindl says, "Neodymium's anticipated flexibility in pulse format as well as its potential for light frequency conversion to a shorter wavelength were strategic reasons for its implementation."

During this time, physicists were also making inroads in target design and, based on experimental data, pivoted to pursue ICF through indirect drive, wherein the laser heats the inside of a cylindrical enclosure called a hohlraum to produce x rays that then irradiate the spherical fuel capsule contained inside the casing. Argus produced up to 4 TW and enabled more extensive radiation-driven experiments, allowing scientists to study laser–plasma interaction (LPI) physics and laser propagation limits in more detail. Argus was also the first laser with integrated spatial filters that were made possible through technology developed by laser scientist John Hunt. The filters help maintain beam quality over long propagation distances, thus reducing optics damage.

Then in 1977, all that was learned from Janus, Cyclops, and Argus came together in the stunning \$25-million, 20-beam Shiva laser. Nearly the size of a football field, Shiva delivered 10.2 kJ of infrared laser light in less than 1 ns during its first full-power firing. Overall, Shiva offered higher power and plasma temperatures, better control over experimental conditions, and greater fuel compression than any previous laser. Two years after it came online, Shiva compressed a fusion fuel capsule to a density 50 to 100 times greater than its liquid density, an unprecedented achievement in laser research.

The 20-beam Shiva became the world's most powerful laser in 1977, delivering an unprecedented 10.2 kilojoules of energy in less than a billionth of a second in its first full-power firing. Shiva's laser bay (shown here) captures the large scale of development taking place by the late 1970s.

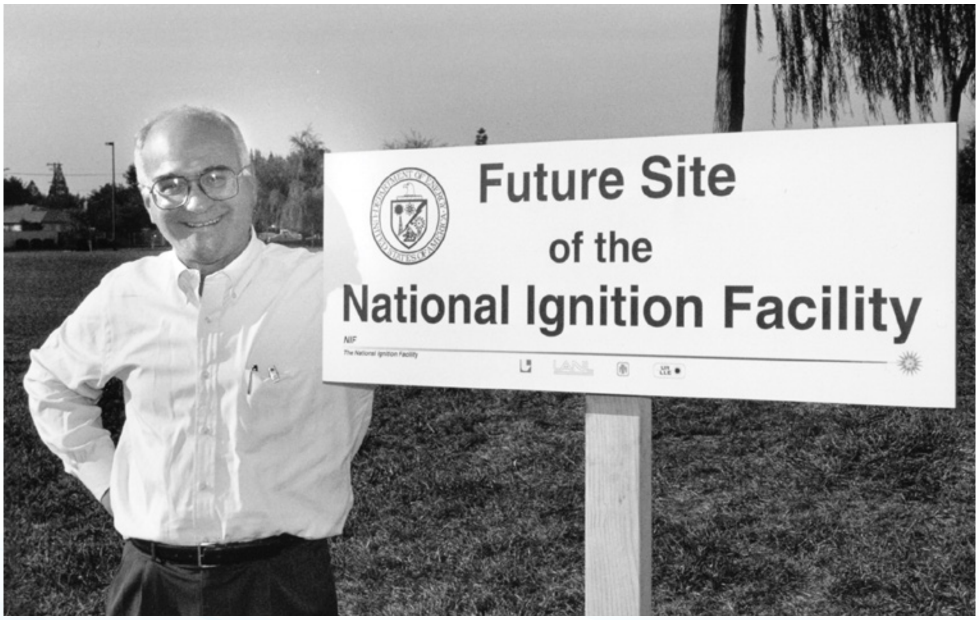
Notably, experiments with Shiva, and early research on Argus, confirmed that a more powerful laser utilizing a different light frequency would be needed to achieve ignition. Early theoretical work, including that by Bill Kruer and Livermore colleagues, indicated that the production of hot electrons from LPIs at the intensities required for ICF might well require laser wavelengths shorter than 1 micrometer (μm). Indeed, the interaction of Argus and Shiva's high-power infrared beams with the hohlraum plasma generated physics that produced a large number of extremely hot electrons and disrupted control over implosion symmetry. Lindl says, "Through demonstration experiments performed on

Argus and additional scaling experiments with Shiva, we concluded a shift to shorter wavelength light was necessary to reach the hohlraum temperatures needed for ignition." Similar experiments on the laser direct-drive approach at LLE and other institutions also showed the need for shorter wavelength light.

With this finding, the Nova laser, in development, was reimagined. Nova's prototype, Novette, was the first multikilojoule system to include a subsystem of plates made of potassium dihydrogen phosphate (KDP) crystals for converting 1-omega (1.053-µm wavelength) infrared light to a higher frequency. Novette experiments carried out with 2-omega (0.53-µm wavelength) and 4-omega (0.265-µm wavelength) light showed that these shorter wavelengths facilitated coupling of the laser energy to the target and reduced laser–plasma instabilities. However, since optics damage becomes a greater challenge with shorter wavelengths, the decision was made to use 3-omega (0.351-µm wavelength) ultraviolet light for Nova. The 10-beam laser produced up to 30,000 J of ultraviolet laser light and 40 TW of power in 2.5-ns pulses. Nova generated the largest laser fusion yield in prior history—a record 11 trillion fusion neutrons—and achieved implosion symmetry sufficient to compress a fuel capsule to about one-thirtieth its original diameter. During this period, Lawrence Livermore's broader weapons program and other institutions began using Nova for a wide range of high-energy-density experiments, demonstrating the utility of lasers for understanding issues important to weapon physics.

Altogether, six large fusion laser systems were engineered and built in 10 years after the Laser Program's inception, and the pace of laser construction matched the growth of diagnostics and target fabrication capabilities, computer simulation tools, and theoretical understanding to continually improve laser capabilities and experimental results. Emmett attributes this success to the people. "We had several hundred people working together in amazing harmony to accomplish something that we all thought was terrifically exciting," he says. "I'd never seen a team work together the way we did."

Nova, which operated from 1984 through 1999, and additional experiments on the Omega laser at LLE, provided the primary experimental basis for the physics of laser-driven, indirect-drive implosions. Coordinated underground explosives tests with Los Alamos would further advance knowledge of the physics required for ignition and demonstrated that although no showstoppers were evident to achieving ICF ignition, an even bigger facility than Nova would be needed to make it a reality. Lindl says, "With Nova at energies below those needed for ignition and the experiments at much larger energies that could be conducted underground, our goal was to bracket the requirements for a future ignition facility."



Vic Reis, then Department of Energy Assistant Secretary for Defense Programs, visits the proposed construction site for the National Ignition Facility (NIF) in 1996. Reis played a key role in the development of the Stockpile Stewardship Program, including plans to build NIF.

A New Era in Laser Research

As the plans for NIF began to take shape, scientists concluded that if they could reach 300 eV hohlraum temperatures, stabilize hydrodynamic instabilities, maintain acceptable LPI effects, and adequately control the capsule's implosion symmetry, then ignition would be possible with a 1 to 2 MJ laser. To make this concept work, NIF would have to go far beyond the performance of what its predecessors could achieve. Laser Program scientists would have to develop an integrated hohlraum and capsule design that could be driven at the needed 300 eV temperatures, and the capsule design had to include a high-quality cryogenic DT layer inside a spherical shell—a central feature of ignition designs.

NIF's development was almost prescient as the changing global landscape of the early 1990s necessitated its delivery. The Soviet Union collapsed, the Cold War ended, and in 1992 U.S. President George H. W. Bush instituted a moratorium on underground nuclear testing—a decision that would have a profound impact on the nation's overall strategy for maintaining the U.S. nuclear weapons stockpile. In the wake of these world-changing events, Vic Reis, in his role as the Department of Energy's (DOE's) Assistant Secretary for Defense Programs, provided the imagination and political acumen to guide the nation's transition to the science-based Stockpile Stewardship Program (SSP).

The program endorsed an aggressive advance in computing capability and the development of key experimental facilities for testing and validating computational models—essential tools for maintaining the safety, security, and effectiveness of an aging and evolving nuclear weapons stockpile without nuclear testing. Nova had demonstrated the utility of lasers for studying weapon physics issues, and NIF would fill a critical mission need in support of SSP. (See *S&TR*, March 2021, pp. 4–11.) Reis's view was that if the Laboratory could sustain the SSP effort and commitment that would be required for ignition, then it would also demonstrate the kind of resolve needed to succeed in the broader SSP mission. Former Laboratory Director George Miller says, "Ultimately, confidence in the stockpile comes down to the confidence in the people making judgements about it. NIF is important both in terms of its ability to make measurements that are important to the stockpile, but equally—and perhaps in some ways more important—its ability to recruit and train people to make decisions about complicated subjects, particularly when you have inadequate knowledge."

Work began in earnest between Livermore and Los Alamos to formally establish the functional requirements and primary criteria for NIF: a laser design capable of providing 1.8 MJ and 500 TW at a laser wavelength of 0.351-µm light; a 192-beam, 4-cone beam geometry consistent with the required target symmetry; precision µm-scale pointing accuracy; and other power-dependent criteria. Scientists in the Laboratory's Laser Program built on their experience with Nova to develop Beamlet, which served as a prototype of the novel multipass architecture designed for NIF that increases the optical energy of each of the 192 laser beams from 1 J to 10 kJ. Beamlet demonstrated that the multipass laser architecture could meet the fluence (energy per unit area) requirements, an accomplishment prescribed by NAS as one of the key developments needed for approval of NIF construction.

Ultimately, given the evidence before it, the NAS committee responsible for reviewing the NIF proposal concluded that the facility had a 50–50 chance of achieving ignition given its specifications, and it would certainly be large enough to firmly establish the requirements for ignition and high gain. Construction had the green light, and groundbreaking began in 1997. Mike Campbell, associate director of the Laser Program at the time, says, "NIF faced many challenges in the early 1990s. We had to develop a strong technical, mission, and stakeholder-support strategy, one that ultimately resulted in official approval for NIF. I still remember after the groundbreaking, walking through building 381 thinking, 'We did it.'" The facility was completed 12 years later, and in March 2009 experiments began as part of the National Nuclear Security Administration's National Ignition Campaign (NIC) to facilitate NIF's transition from a construction project to a national user facility.

Missions "Seemingly" Impossible

Lawrence Livermore was founded as a "new ideas Laboratory" in 1952. From the beginning, its purpose was to pursue innovative solutions to the nation's pressing needs, particularly to advance nuclear weapons science and technology during the Cold War. "The whole point of having places like the Laboratory is to do things that are incredibly difficult," says Lawrence Livermore Director Kimberly Budil. "We're here to take on the biggest, most gnarly technical challenges that our country and the world face." Indeed, Edward Teller, one of the founders of the Laboratory, proved early on that Livermore never shied away from tasks deemed impossible.

In the summer of 1956, the U.S. Navy sponsored an interagency study on antisubmarine warfare that led to discussion of whether it was possible to make a small, light, nuclear warhead in the 1-megaton range. When Teller recalled the event decades later, he said, "Everyone at the meeting, including representatives from Los Alamos, said it could not be done—at least in the near future. But I stood up and said, 'We at Livermore can deliver it in five years, and it will yield 1 megaton.'" Upon hearing the news, his Laboratory colleagues were incredulous. He continued, "They said, 'What have you done? We can't get a megaton out of such a small device, not in five years!'"

Yet, remarkably, in a three-year crash effort, Livermore scientists and engineers made sweeping technological breakthroughs to develop the highly effective W47 Polaris warhead in record time. Fast forward to today, and that same fighting spirit and superior ingenuity puts Livermore once more on the verge of a scientific accomplishment many deemed impossible: fusion ignition and gain.

Necessity: The Mother of Invention

From a technology standpoint, NIF was a giant leap. NIF produces 60 times as much energy with 10 to 20 times more power than Nova. The size of three football fields, NIF is the world's most energetic high-energy laser system, serving as a unique capability to advance ICF research, astrophysics, and planetary science; support stockpile stewardship and radiation effects experiments; and investigate the potential for controlled fusion as an energy source. The laser system accurately guides, amplifies, reflects, and focuses all 192 laser beams onto a centimeter-scale hohlraum containing a millimeter-scale fusion target in just 1 ns, delivering up to 2 MJ of ultraviolet energy and 500 TW of peak power. NIF implosions have generated temperatures in the target of more than 180 million degrees Fahrenheit (about 9,000 eV) and pressures of more than 300 billion Earth atmospheres, conditions that exceed those at the center of stars.

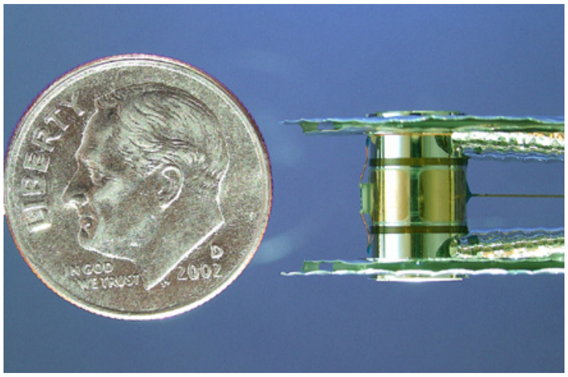
Ed Moses, NIF project manager from 1999 to 2005 and later Principal Associate Director for NIF & PS, says, "NIF was not an incremental advance. It was approximately a factor of a hundred more than Nova, and few institutions will take that kind of step. When I came to NIF, we looked at what NIF was; what it was being asked to do; and how it was being stressed from a science, technology, engineering, and management point of view; and we recognized important challenges that we had to face." The NIF team worked closely with industrial partners, in some cases for more than a decade before the project began, to advance technologies needed to complete NIF. Among those accomplishments are the so-called seven wonders of NIF: precision preamplifier modules that shape, smooth, and intensify

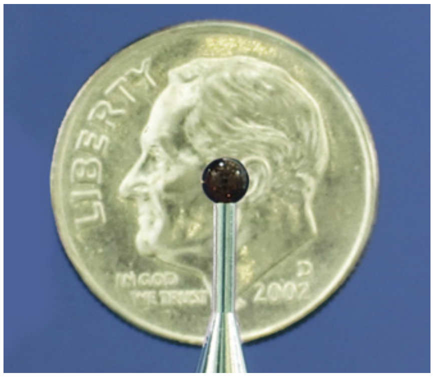
Beamlet, the single-beam prototype for NIF, demonstrated that the multipass laser architecture developed for NIF could meet the fluence (energy per unit area) requirements prescribed by the National Academy of Sciences.

laser light; continuous-pour laser glass for faster, less expensive glass production; rapid-growth KDP crystals; optical switches that work in conjunction with the amplifiers to increase the beams' energy; deformable mirrors to correct for wavefront errors; an integrated control system for conducting shots; and advanced manufacturing capabilities for target fabrication. In tandem with this work, the NIF team devised new experimental platforms and a vast array of optical, x-ray, and nuclear diagnostics for characterizing each experiment. (See *S&TR*, December 2010, pp. 12–18.)

In collaboration with partners including Los Alamos and Sandia; LLE; MIT; General Atomics; National Security Technologies, LLC; and the atomic energy agencies in the United Kingdom and France, Livermore scientists and engineers have created a suite of more than 120 diagnostics for characterizing experiments in unprecedented detail, and the number continues to grow. Vice President at General Atomics and NIF measurements lead Joe Kilkenny, says, "The quality of the diagnostics enables the high-quality science, and this is particularly true with NIF. We have achieved innovation and quality through a national diagnostic effort, drawing from the best ideas from each of the partner institutions."

Dedicated, collaborative research and development in target fabrication between Livermore, General Atomics, and Diamond Materials allowed major advances that ultimately led to production of ultrasmooth beryllium, high-density-carbon (HDC, or diamond), and plastic shells to provide ablators and stable uranium hohlraums, along with the associated precision metrology, which have all proven crucial for the ICF effort. Target engineering innovations led to the development of a robust platform for making full cryogenic targets while increasing cryo-target throughput to provide sufficient targets for the needed shots.





ICF requires perfecting technologies that span a dramatic range of spatial scales. The facility (top) is the size of three football fields and focuses 192 laser beams into a centimeter-scale hohlraum (bottom left) containing a millimeter-scale fusion capsule (bottom right), which is then compressed by a factor of 30 to a diameter comparable to that of a human hair. (U.S. dime shown for scale.)

Alongside these advances, the ICF team has also promoted the development of advanced computer codes that help guide experiments. For example, the Hydra code utilizes the unprecedented large-scale computing hardware and various software libraries developed by the Laboratory's Advanced Simulation and Computing (ASC) Program to generate 3D simulations of ICF capsules and hohlraums.

Hydra, together with exceptional ASC computational resources, has played a critical role in improving physics understanding on the path to ignition.

Another 10 Years of Innovation

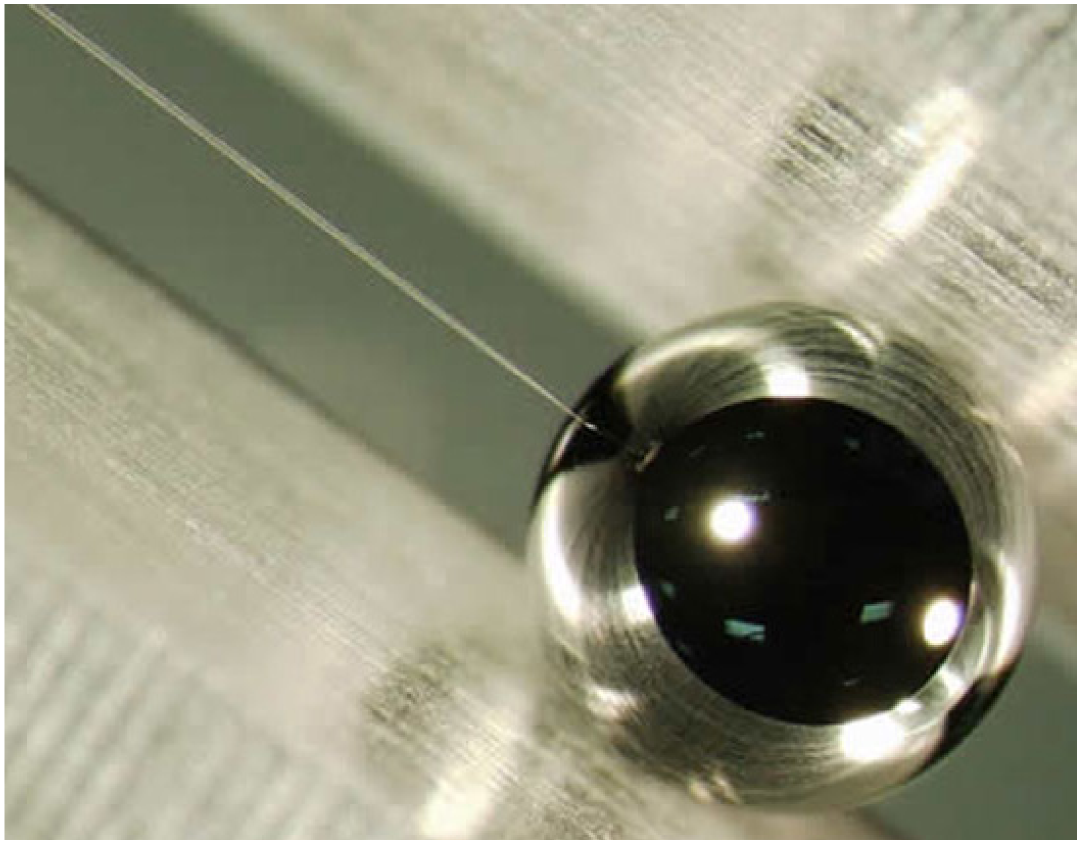
Since 2009, when experimental operations began, NIF scientists and engineers have continually improved the laser's performance, tuning, accuracy, and shot reproducibility, among other capabilities. (See *S&TR*, March 2013, pp. 10–17.) During NIC, which ended in 2012, the NIF team installed and qualified many target diagnostics, facility capabilities, and experimental platforms; implemented a target positioner diagnostic for fielding cryogenic DT layered targets; determined how to make high-quality DT ice layers; implemented target fabrication capabilities to meet the stringent requirements; and advanced the final optics sufficiently to deliver more than 1.8 MJ and 500 TW. Mary Spaeth, NIF chief technologist from 1999 to 2012, says, "NIF fully meets its original design requirements. After solving all the challenging design and engineering problems for building NIF, the final key for meeting its power and energy goals has been the ability to recycle and repair its damaged optics for continued use in the laser."

A large ICF laser system must provide both energy and power on target, while delivering that energy with wide variations in pulse shape. Follow-on experiments after NIC led physicists to investigate modifications to the laser pulse as a means of improving implosion symmetry and overall target performance. Researchers made a breakthrough in 2013 when they conducted an experiment using a "high-foot" pulse shape—three shocks characterized by a higher power initial pulse and shorter pulse duration (15 ns versus 20 ns) compared to the previous "low-foot" pulse specifications. (See *S&TR*, June 2014, pp. 4–10.) "The high-foot design tested the hypothesis that ablation Rayleigh–Taylor instability was a performance-limiting factor during the NIC experiments and that by better controlling it, we could make a step to higher fusion performance," says chief scientist Omar Hurricane. "These experiments were extremely exciting as we obtained more than an order of magnitude increase in fusion yield performance in a half-a-dozen DT experiments and obtained the first experimental demonstration of alpha-heating and fusion fuel gain."

Both the high-foot and earlier low-foot shots used hohlraums with helium gas fill to slow down the inward expansion of the cylinder's walls during the experiments. In 2013, experiments showed that reducing this gas fill by a factor of 3 to 5 dramatically reduces LPI effects in the hohlraum. However, a reduced gas fill shortens the pulse lengths that can be utilized for NIF before control over implosion symmetry is lost. To utilize the lower gas fill more effectively, scientists switched from plastic capsules to HDC ones. Reductions in the size of the tiny fill tubes used to inject the DT fuel into the capsule also paid dividends. To reduce the x-ray emissions from fill-tube material injected into the compressed fuel, scientists at General Atomics reduced the size of the fill tubes from 10 to 5 µm in diameter, and ultimately to 2 µm (for comparison, the diameter of a human hair is approximately 70 µm) and achieved up to double the neutron yield.

Through the tandem paradigm and iterative process of experiments and simulations, bolstered by data captured from the ever-growing number of diagnostics and techniques, scientists

Target Area Operator Bill Board removes an image plate from the NIF Dilation X-ray Imager (DIXI), the world's fastest x-ray framing camera. It produces images of an imploding target capsule with 10 times faster temporal resolution than previous systems. DIXI is one of 120 NIF diagnostics developed for characterizing experiments in unprecedented detail. (Photo by James Pryatel.)



Scientists reduced the size of the fill tubes—used to inject the deuterium–tritium fuel into the capsule—from 10 to 2 micrometers (µm) in diameter. Shown here is the 2-µm fill tube (thin needlelike object) inserted into a high-density-carbon capsule. The significant decrease in size improved the implosion symmetry of the target and doubled the neutron yield. (Photo courtesy of General Atomics.)

have and continue to make great strides in understanding and enhancing laser tuning, pulse shaping, and target components and construction. "We're constantly improving the capability of the laser from the standpoints of how much energy and power we can generate, the precision with which we can deliver it, and how we can diagnose the experimental output. We also continually engineer improvements to operational efficiency, identifying anything that will make NIF more productive for the programs," says NIF Director Doug Larson. Now, the insights and improvements made in the last 10 years have brought NIF to the edge of what it was built to do.

A Major Fusion Milestone

On August 8, 2021, NIF laser beams imploded a target capsule to create a central hot spot of dense DT fuel and trigger a self-sustaining wave of fusion reactions. This historic experiment achieved a record ICF yield of more than 1.3 MJ of fusion energy, a yield from the imploding capsule about six times the x-ray energy it absorbed. As defined by NAS, ignition occurs when the fusion energy produced exceeds the amount of laser energy delivered to the target chamber. The measured fusion yield

Hybrid-E experimental lead Alex Zylstra (left) and target design lead Annie Kritcher stand in the NIF target bay holding a Hybrid-E target. This target design was used in the record-breaking fusion shot at NIF on August 8, 2021. (Photo by Mark Meamber.)

was about 70 percent of that goal. The laser system delivered 1.9 MJ, which squeezed the central DT fuel within the capsule to eight times the density of lead and generated more than 10 quadrillion watts of fusion power for 100 trillionths of a second.

This experiment brings NIF shots into a fundamentally new physics regime with signatures of a hotspot undergoing rapid self-heating and beginning to propagate burn into the surrounding dense shell, which causes increases in fusion yield, temperature, hotspot mass, and energy. This shot produced eight-times higher yield than the previous NIF record and 25-times higher yield than was achieved prior to November 2020. "An incredible amount of teamwork got us to this point," says former NIF Director Mark Herrmann, now director of the Laboratory's Weapon Physics and Design Program, "from conceiving of ICF 60 years ago in the revolutionary work by John Nuckolls to developing a series of lasers; advancing optics, target fabrication, computer simulations, and designs; understanding the science; and fielding the diagnostics that allow us to measure these extraordinary events."

The success of the result relied on extensive efforts during the year to improve the target design (called Hybrid-E), which includes a large HDC capsule and the 2-µm-diameter DT fill tube. NIF Target Fabrication Program Manager Abbas Nikroo says, "Changes to the HDC deposition and polishing processes allowed major improvements in the quality of HDC shells where capsule defects were reduced by two orders of magnitude—a key target fabrication improvement that, combined with the innovative hohlraum drive, enabled this significant achievement."

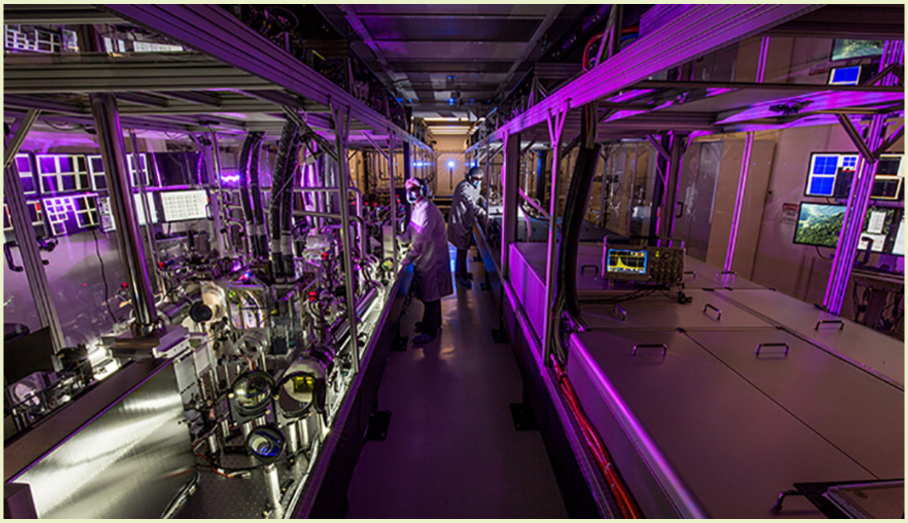
Compared to earlier NIF experiments, Hybrid-E uses a larger capsule and a more efficient hohlraum to couple more energy to the compressed fuel resulting in an increase in hotspot pressure and temperature. "A major challenge in increasing the coupled energy to the hotspot by making the implosion larger with the fixed laser energy and not reduce the hotspot pressure was to carefully balance and optimize many design parameters simultaneously," says Hybrid-E lead designer Annie Kritcher. To achieve a symmetric implosion with the larger capsule, the wavelength of each laser beam is slightly adjusted to help balance x-ray energy that drives the implosion. The entrance holes that let

Technology Development through Fusion Research

Over its 50-year history, the Laboratory's Laser Program has developed many high-profile spin-off technologies from inertial confinement fusion (ICF) research. The field of laboratory astrophysics was born during Nova's era (1984–1999) and has enabled scientists across the world to study astrophysical phenomena in greater detail. The emergence of short-pulse lasers, including the world's first petawatt laser on Nova, extended astrophysics work to relativistic regimes and other applications including plasma-based, high-energy particle acceleration. Short-pulse lasers also spurred the broader area of high-field physics.

Extreme ultraviolet lithography—developed from Livermore's early work with precision engineering, metrology, and coatings—supported the continuation of Moore's Law, driving ever-smaller and faster microprocessors. Optical technologies developed by the Laser Program include high-damage-threshold silica, gratings, and coatings. Laser applications advanced metal conditioning (peening) to increase the strength and lifetime of high-stress components such as jet turbine blades. An outflow of target diagnostic work on Nova led to micropower impulse radar, which was extensively licensed for use in automotive cruise control, tape measures, stud finders, and many other products.

The rich history of the Laser Program includes many other examples that illustrate the contributions of ICF research. In the years to come, continuing to improve the flexibility, power, and precision of the National Ignition Facility will spur further technology advances that will impact science and industry well beyond ICF.



High-repetition-rate lasers, such as the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS)—the world's most advanced and highest average power diode-pumped petawatt laser—have been made possible through ICF research.

laser light into the hohlraum were also reduced in size to increase the coupled energy. The experiment used one of the highest quality target capsules ever shot at NIF, with a surface virtually free of pits and voids and 99.7 percent shell thickness uniformity.

With the August 8, 2021, shot, improvements to establish better reproducibility enabled the laser to deliver a pulse very close to the target design specifications. “There was a certain amount of serendipity in the 1.3-megajoule experiment. It required more than a good design concept. It needed a high-quality target, a precise laser pulse, and uniform energy delivery—all those things coming together synergistically to achieve the result,” says Laboratory Director Kimberly Budil. “We are squarely on the threshold of ignition, and well positioned to take the next steps toward target gain greater than one and beyond. The goal is to create a stable, repeatable, robust, igniting platform, and our entire team is hard at work to make this possible.”

Lawrence Livermore Director Kimberly Budil (far left) served as moderator for the opening panel of the White House Fusion Summit on March 17, 2022. The first-of-its-kind summit convened leaders in fusion from government, industry, and academia to showcase the latest fusion achievements and technologies and discuss an inclusive, equitable 10-year strategy for developing commercial fusion energy.

The Future of Fusion

NIF’s breakthrough experiment factored heavily in discussions during a recent White House Fusion Summit. Hosted by the White House Office of Science and Technology Policy and by DOE, the first-of-its-kind summit convened leaders in fusion from government, industry, and academia to showcase the latest fusion achievements and technologies and discuss a 10-year strategy for advancing development of commercial fusion energy.

Director Budil was requested to host a panel as part of the event. “We discussed where we are with fusion research based on results from NIF, tokamaks, new kinds of superconducting magnets, progress on ITER, and the work that still needs to be done,” says Budil. “Several billion dollars in investments have been made in this area over the last year, and the goal is to build a demonstration plant to show that commercial fusion energy is viable. We have the only facility on the planet right now that can pursue the science to develop a stable, repeatable, igniting platform in the laboratory.”

Together, the NIF team has constructed, tested, and fine-tuned an unprecedented laser facility. This achievement is the result of the decades of work in laser technology, target fabrication, diagnostics, and computer modeling developed through each of Livermore’s major laser systems over 50 years of programmatic research. NIF Operations Manager Bruno Van Wonterghem says, “We’ve all made sacrifices to get here, but it is worth it to stand here now in a structure that many said could never be built, as it performs on a day-to-day basis what many believed it couldn’t.”

Producing an ignited fusion plasma in a laboratory is indeed a scientific grand challenge but when attained will provide new avenues of scientific exploration. “Fusion is one of those fundamental processes of mother nature. It’s the energy source of the universe,” says Jeff Wisoff, principal associate director for NIF & PS. “Being able to control that process in a laboratory and use it someday would be one of the major milestones of human history, like gaining fire.”

—Caryn Meissner

(Additional resources provided by John Lindl and Paul Chrzanowski)

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For further information contact Patti Koning (925) 423-4332 (koning3@llnl.gov).